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EVALUATION OF WINDOW FAILURE MODES

FINAL REPORT
DECEMBER 1999

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Washington, DC 20593-0001

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16. Abstract (MAXIMUM 200 WORDS)

A furnace test was conducted to investigate a possible cause of premature failures of one-hour fire-rated window assemblies in a previous test series. In the previous series, two of the four A-30 window assemblies and one of the four A-60 window assemblies failed within eight and ten minutes after the beginning of the test exposure. A suspected cause was damage by welding slag from the attachment of the thermocouples to the window frame.

To investigate the suspected cause, the unexposed face of an A-30 window assembly was damaged using welding slag. One damaged window assembly fractured when it was installed in the test bulkhead. A second A-30 window was damaged using welding slag and tested side by side with an undamaged A-30 window. Both windows performed similarly without failure. Thus, damage from welding slag is unlikely to be the cause of the premature failures in the previous test series.

The fire test followed Resolution A.754(18) of the International Maritime Organization with some exceptions. The main exception was termination of the test after 35 minutes.

The window frames in this test were not the same design as those in previous test series due to unavailability.

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EXECUTIVE SUMMARY

This test program is a continuation of the U.S. Coast Guard (USCG) program element 3308.2.74, Fire Resistance of Divisions (Radiation). Previously, the USCG conducted a series of furnace tests of a type of A-0 windows, a type of A-30 windows, and a type of A-60 windows.[1] The A-30 and the A-60 windows were constructed using Contraflam gel sandwiched between glass. The window frame was a design that was approved by Lloyd's Register for A-60 windows. The A-60 windows had been approved by the Canadian Coast Guard. In these tests, an A-30 specimen and an A-60 specimen were mounted side by side in an insulated bulkhead and simultaneously tested. Two out of four A-30 windows and one out of four A-60 windows exhibited early failure. An exact cause of these failures was not determined, and the work effort reported herein was to investigate the potential failure modes.

The postulated failure modes were incorrect installation (i.e., upside down) or damage from welding slag. The first failure mode (improper installation) could not be evaluated. The manufacturer of the window frame assembly used in the previous test series had discontinued this type of window frame. In addition, other window frames available for use were constructed such that the window assembly did not have a specific top or bottom (i.e., could be installed in any manner). Since the exact window frame assembly was not available, a test with improper installation could not be accurately performed, and thus, no further testing or analysis on this failure mode was performed.

The approach to evaluate the second postulated failure mode (i.e., damage) was to perform full-scale fire resistance tests. Two tests were to be conducted. In each test, one damaged and one undamaged A-30 type window assembly would be evaluated. The incorporation of the undamaged window assembly would provide a control in each test. The window assemblies were approved A-30 type windows. In the case of the damaged windows, welding slag was used in an attempt to reproduce the damage noted in the earlier test series.

[1] The A rating indicates that a boundary will resist the passage of flame for one hour. The following number indicates the duration that a boundary will not exceed the limit on temperature rise on the unexposed side. Thus an A-30 window will resist the passage of flame for one hour and not exceed the limit on temperature rise for at least 30 minutes in the standard test.

Initially, one window was selected for damage. The damage consisted of pits into the face of the glazing, and this was accomplished by arc welding on a piece of steel placed above a horizontal window assembly. As this window was being installed, it fractured and was not usable for further testing. A second window assembly was mounted into the test bulkhead and was damaged just prior to the test with the window assembly in the vertical orientation. A subsequent fire resistance test that incorporated both a damaged and an undamaged window assembly was conducted. The test was conducted in accordance with "Recommendation on Fire Test Procedures for 'A,' 'B,' and 'F' Class Divisions (IMO Resolution A.754(18))."

During the test, the exposed layer of glass did fracture and fall from both of the assemblies. The gel did react to the heat, and it formed a char layer. The glass on the unexposed face of both window assemblies did not fracture or fall away. From the temperature data and the observations, both of the test windows met the A-30 requirement of limiting the temperature rise for 30 minutes.

Based on these test results, as well as the lack of a fourth window (i.e., fractured earlier, thus no control window was available), it was decided that a second test would not be performed.

The results of this fire test did not substantiate the theory that welding splatter would cause a premature failure as occurred in the earlier testing. However, the failure of a window assembly during its mounting in a bulkhead indicates that the extent of the damage (i.e., size and depth of pits) may be a significant factor with respect to its performance.

The test also indicates that an A-30 window assembly may perform appropriately even with some damage on the unexposed face of the glass.

Based on this work and since the other postulated failure mode (i.e., incorrect installation) was not evaluated, no definitive conclusion can be drawn concerning the failures observed in the previous testing.

Table of Contents

Page

List of Figures

List of Tables

INTRODUCTION

This test program is a continuation of the U.S. Coast Guard (USCG) program element 3308.2.74, Fire Resistance of Divisions (Radiation). Previously, the USCG has conducted a series of furnace tests of a type of A-0 windows, a type of A-30 windows, and a type of A-60 windows (Sheppard, 1997).[2] The A-30 and the A-60 windows were constructed using Contraflam gel sandwiched between glass. The window frame was a design that was approved by Lloyd's Register for A-60 windows. The A-60 windows had been approved by the Canadian Coast Guard. In these tests, an A-30 specimen and an A-60 specimen were mounted side by side in an insulated bulkhead and simultaneously tested.

In the first A-30 and A-60 test, the A-30 window shattered at eight minutes into the test, and the A-60 window shattered at nine minutes into the test. These early failures were attributed to improper installation of the windows (i.e., upside down).

In the second test, both the A-60 and the A-30 windows remained in place for a duration of 60 minutes.

In the third test, the A-30 shattered at eight minutes into the test period. The A-60 window had no openings when the test was terminated at 22 minutes. Neither window was installed upside down, but the A-30 window may have been damaged due to welding slag that came from mounting thermocouples. This type of damage was noted on an untested sample, and it is thought that this may be the cause for the early failure of the A-30 window.

In the fourth test, both the A-30 and the A-60 windows remained in the opening for 60 minutes.

[2] The A in A-X rating indicates that a boundary will resist the passage of flame for one hour. The X indicates the duration in minutes that a boundary will not exceed the limit on temperature rise on the unexposed side. Thus an A-30 window will resist the passage of flame for one hour and not exceed the limit on temperature rise for at least 30 minutes in the standard test.

In summation for the previous test series, two out of four A-30 windows and one out of four A-60 windows exhibited early failure. An exact cause of these failures has not been determined, and the work effort reported herein was to investigate the potential failure modes.

OBJECTIVES

The objective of this effort was to investigate whether catastrophic premature failure of A-30 windows could be caused by incorrect installation or damage from welding slag. This investigation was conducted using A-30 windows exposed to full-scale fire resistance tests.

APPROACH

The postulated failure modes were incorrect installation (i.e., upside down) or damage from welding slag. The first failure mode (improper installation) could not be evaluated. The manufacturer of the window frame assembly used in the previous test series had discontinued this type of window frame. In addition, other window frames available for use were constructed such that the window assembly did not have a specific top or bottom (i.e., could be installed in any manner). Since the exact window frame assembly was not available, a test with improper installation could not be accurately performed, and thus, no further testing or analysis on this failure mode was performed.

The approach to evaluate the second postulated failure mode (i.e., damaged) was to perform full-scale fire resistance tests. Two duplicate tests were to be conducted. In each test, one damaged and one undamaged A-30 type window assembly would be evaluated. The incorporation of the undamaged window assembly would provide a control in each test. The window assemblies would be approved A-30 type windows. In the case of the damaged windows, welding slag would be used in an attempt to reproduce the damage noted in the earlier test series.

EXPERIMENTAL

Overall

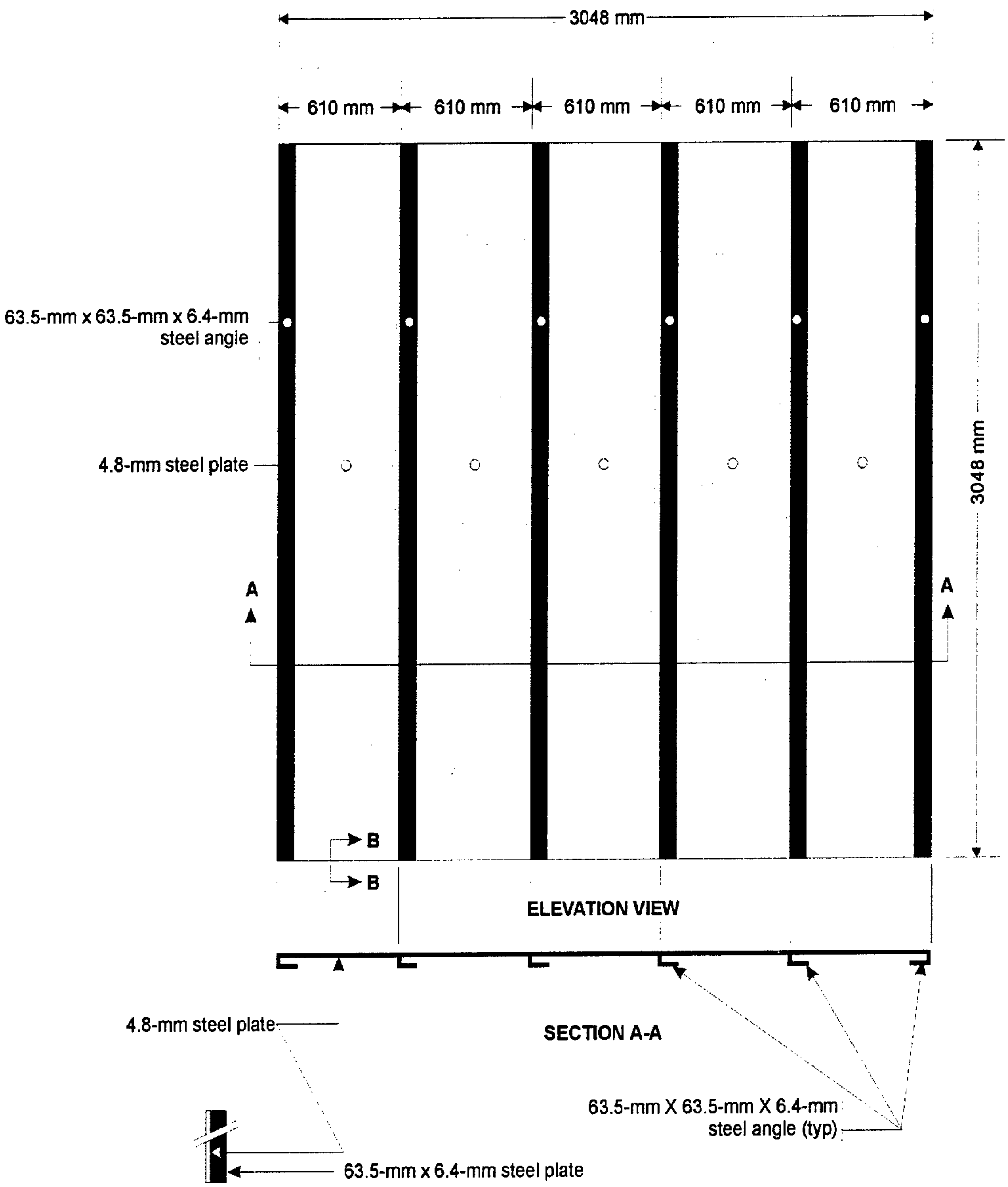
Based on the approach described above, two fire resistance tests were planned. Omega Point Laboratories, Inc., located in San Antonio, Texas, was the test laboratory, and the Cornell-Carr Company, Inc., located in Monroe, Connecticut, manufactured the test window assemblies. The window assemblies consisted of Cornell-Carr's window frame and a Contraflam gel glazing system purchased from a supplier. Neither Omega Point Laboratories nor Cornell-Carr Company were involved in the test series described in the introduction.

The two tests would be conducted in general accordance with the "Recommendation on Fire Test Procedures for 'A,' 'B,' and 'F' Class Divisions (IMO Resolution A.754(18))" (IMO, 1998a). Specific details are provided below.

Test Bulkheads

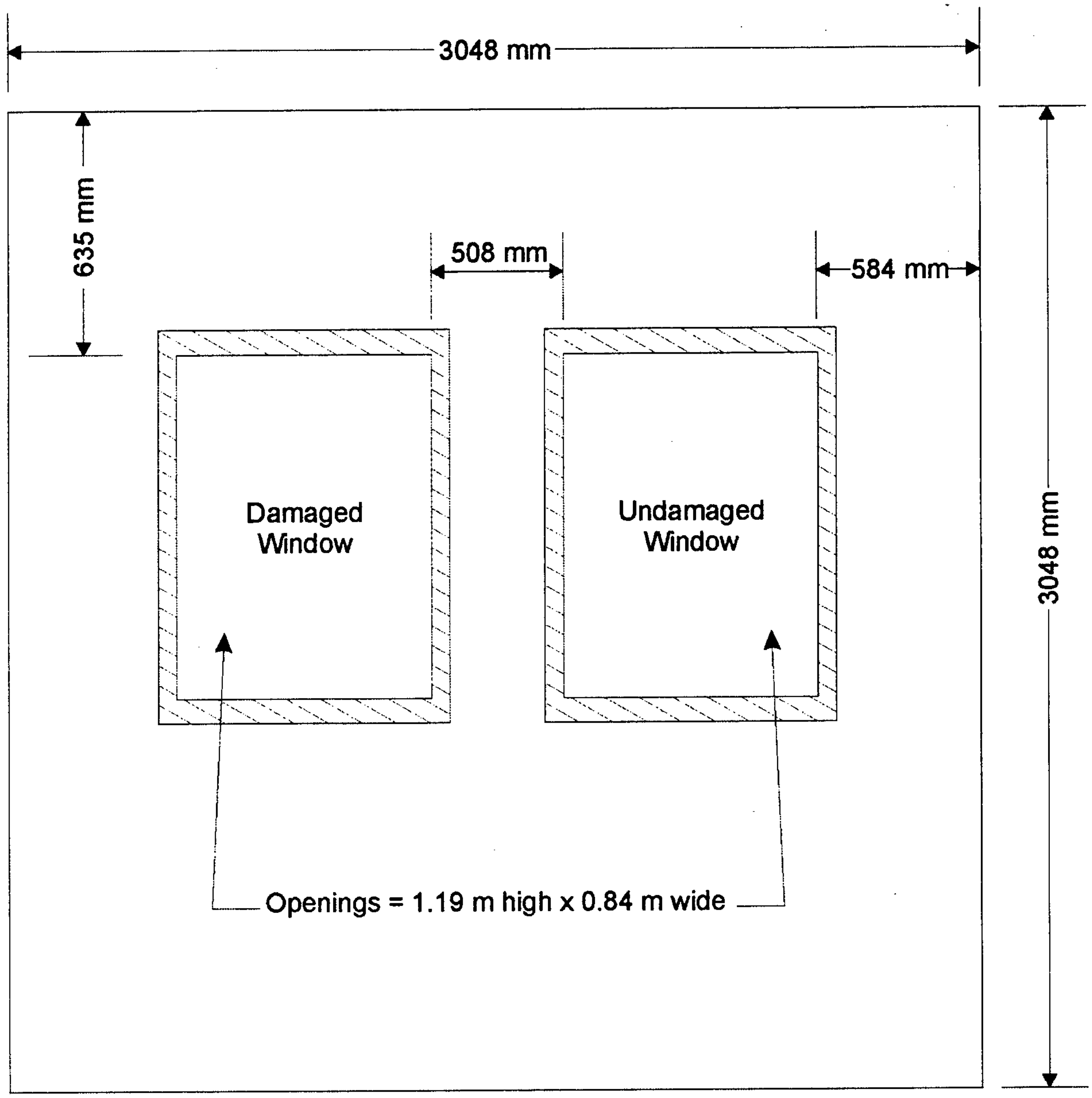
Two standard A-60 IMO bulkheads were constructed. Each test bulkhead was installed in a test frame such that all four edges of the bulkhead were restrained. Details of the test bulkheads are provided in Figure 1. Each bulkhead was constructed of nominal 4.5-mm (3/16-in) thick steel plate. The steel plate had the joints continuously welded from one side. The overall dimensions of the bulkheads were 2480 mm high and 3020 mm wide. The bulkheads had six 65 x 65 x 6 mm stiffeners. The stiffeners ran the height of the bulkheads, and the attachment (welding) of the stiffeners was as shown in Figure 1.

Each bulkhead had two openings as shown in Figure 2. After installation of the test window assemblies into these openings, the bulkhead was insulated on the fire exposed (stiffener) side. The insulation consisted of two 25-mm (1-in) thick layers of 128-kg/m^3 (8-pcf) ceramic fiber insulation held in place by impaling on 102-mm (4-in) long insulation pins, spaced nominally 304 mm (12 in) on center. The insulation was secured to the pins using 30.5-mm (1.2-in) x 38.1-mm (1.5-in) square steel speed clips. All joints were offset by a minimum of 304 mm (12 in). The insulation provided an A-60 type bulkhead assembly.



Note:
The steel bulkhead consisted of 4.8-mm steel plate, continuously welded on one side, reinforced with 63.5-mm x 63.5-mm x 6.4-mm steel angle stiffeners, positioned 610-mm o.c. as indicated. The top and bottom were reinforced with 63.5-mm x 6.4-mm steel plate as shown.

Figure 1. Bulkhead construction.



ELEVATION VIEW
UNEXPOSED SIDE

Note:
The two windows were mounted to the smooth (non-stiffener) side of the bulkhead by placing a gasket between the frame and the bulkhead and bolting each window assembly to the bulkhead.

Figure 2. Bulkhead window openings.

A-30 Window Assemblies

The window assemblies were supplied by Cornell-Carr Company, Inc., and their construction is detailed in figures 3 and 4. The glazing consisted of two panes of 6-mm thick tempered glass with a 28-mm thickness of Contraflam insulating gel sandwiched between the two layers of glass. The overall thickness of the glazing was 40 mm. Each pane was 1190 mm (46.85 in) high by 840 mm (33.07 in) wide.

The window frames were commercial marine grade construction for A-Class windows aboard ships. The window frame consisted of a channel system designed with a multiple layer system of insulation and spacers. The frame utilized insulation that acted as both insulation and a cushion between the window frame and the glazing.

Cornell-Carr Company, Inc. manufactured the steel window frame and mounted the glazing into the frame. The complete window assembly was then shipped to the test laboratory.

The window assemblies were mounted using predrilled holes in the frames and the bulkhead. A gasket material (ceramic fiber) was placed between each window, and the bare bulkhead steel and the windows were securely bolted to the bulkhead.

Window Damage

Two of the window assemblies were damaged using welding slag since the failure mode under consideration in this test series involved damage of the tempered glass by welding slag. Since the postulated failure mode was that the damage to the glazing occurred during the installation of thermocouples, the unexposed side of the window assembly would be damaged. Initially, it was planned to damage the glazing on the unexposed side in one test and to damage the glazing on the exposed side in the other test. The data obtained from these two tests would assist in providing guidance for future installations.

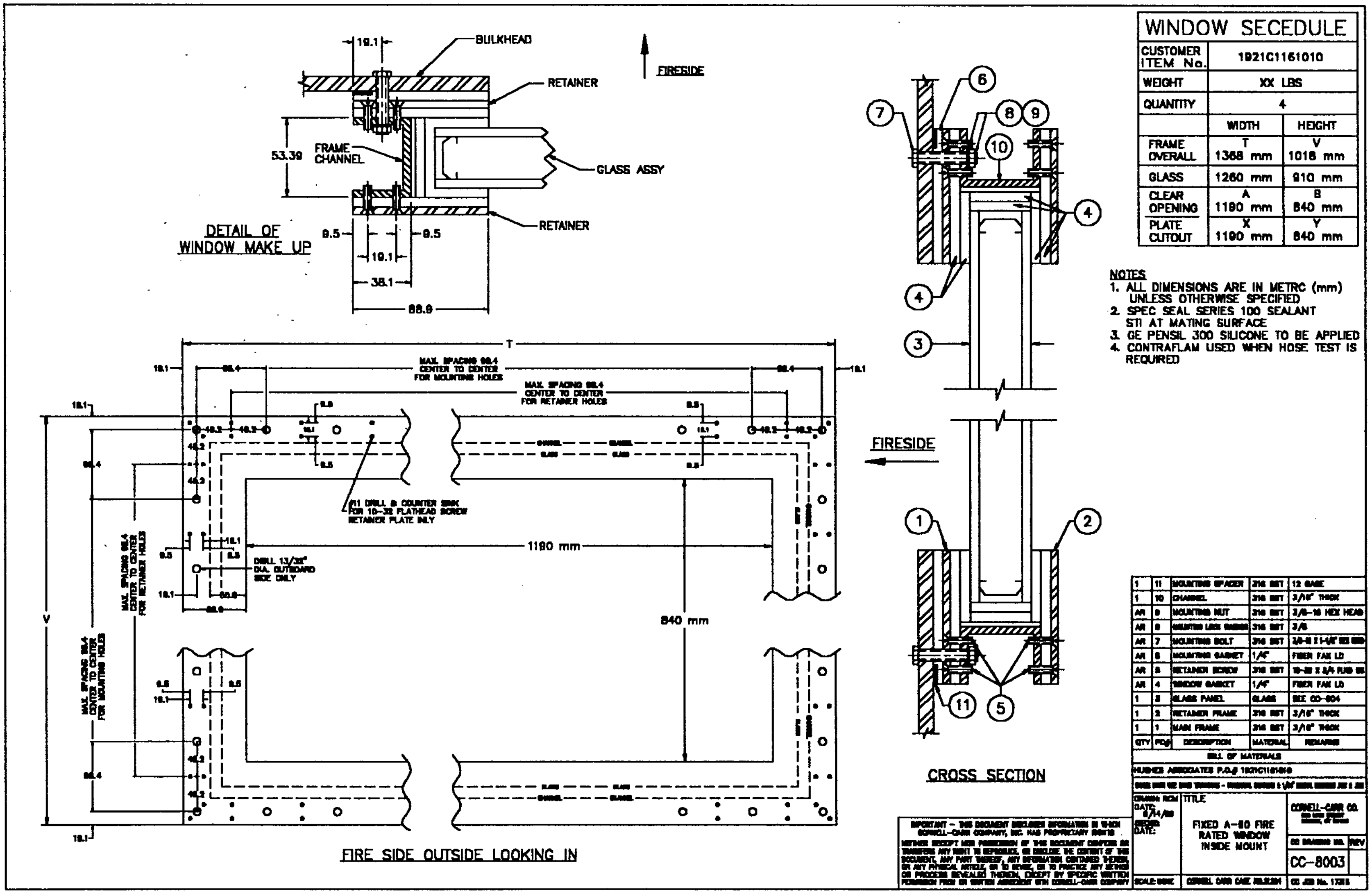


Figure 3. Drawings of the window assembly reproduced with permission of Cornell-Carr Company.

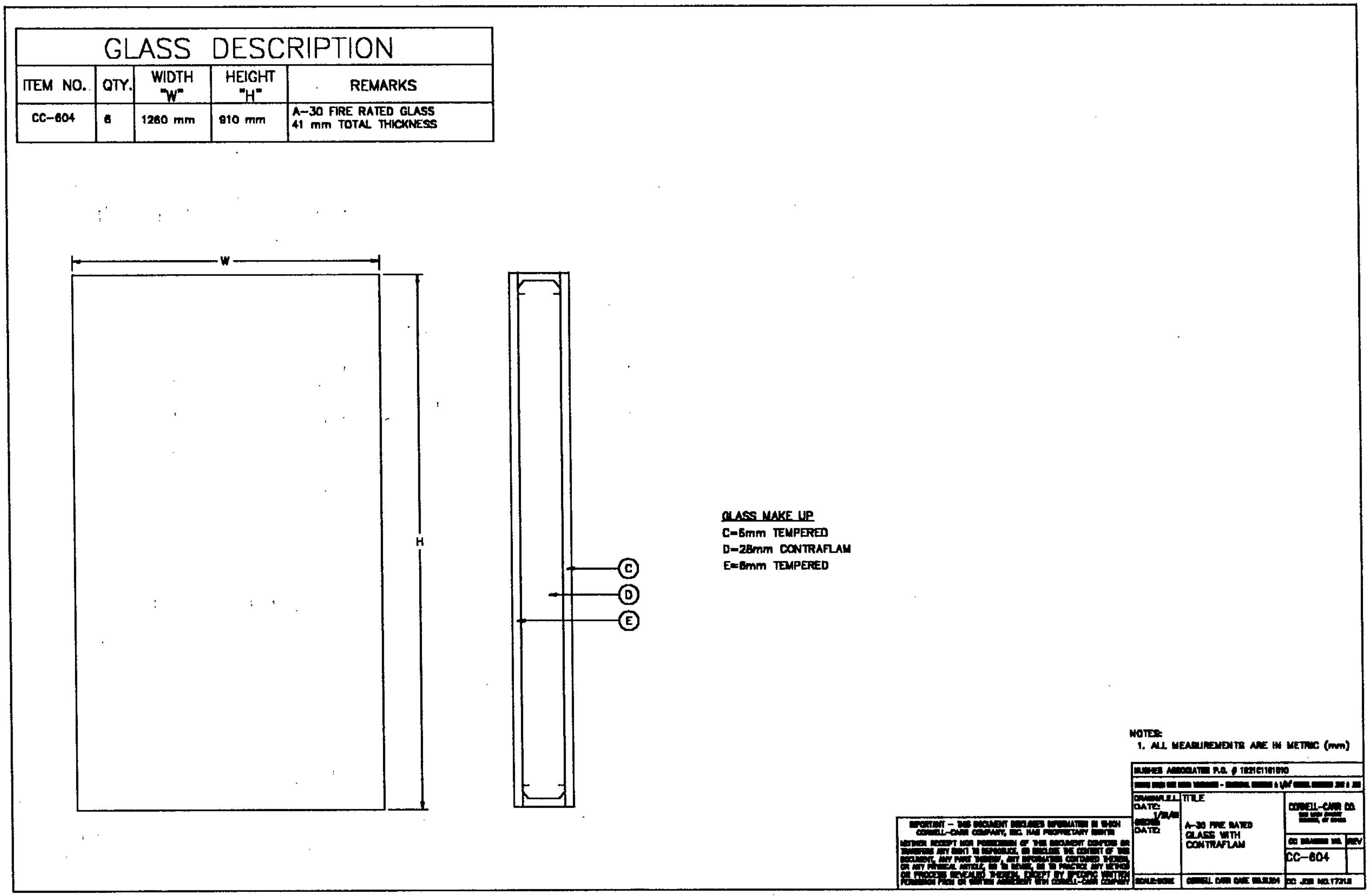


Figure 4. Drawing of the glazing reproduced with permission of Cornell-Carr Company.

Prior to actually damaging a window assembly, a separate piece of glazing was used for experimentation. Welding slag was produced via standard arc welding and a plasma cutter. It appeared that the arc welding would produce sufficient amounts of hot slag, which would impact the tempered glass, and due to their heat, cause pits to occur in the surface of the glass.

Prior to its installation in the bulkhead, one of the window assemblies was damaged using welding slag. This was accomplished with the window assembly in a horizontal position, and the arc welding (using a steel plate) above the top surface of the window assembly. This resulted in pitting of the tempered glass on the side to be exposed to the fire. figure 5 provides a photograph of the arrangement, and figure 6 provides a photograph of the damage. During the mounting of this window assembly, the damaged face of the window assembly completely fractured. figure 7 provides a photograph of the fractured glazing. It was deemed that this window assembly was not usable for further testing, and it was removed from the bulkhead.

A second window assembly was selected for damage. In this case, the window was initially mounted into the test frame prior to damage. Once the window was properly installed in the bulkhead, the arc welding technique used to damage the first window assembly was again used, but the welding was performed in the vertical orientation. Again, damage to the glazing was accomplished (see figure 8), but it appeared that the damage to the glazing did not penetrate the glass to the depth that was noted in the first window assembly. In this instance, the window assembly was damaged on the side not directly exposed to the fire (unexposed side).

Test Method

The fire testing was conducted in accordance with the "Recommendation on Fire Test Procedures for 'A,' 'B,' and 'F' Class Divisions (IMO Resolution A.754(18))" with the following clarifications, additions, and exceptions.

- The surface thermocouple locations specified in Appendix A.1 of IMO Resolution A.754(18) were used.
- The hose stream test in accordance with paragraph 5 of Appendix A.1 of IMO Resolution A.754(18) was not performed.

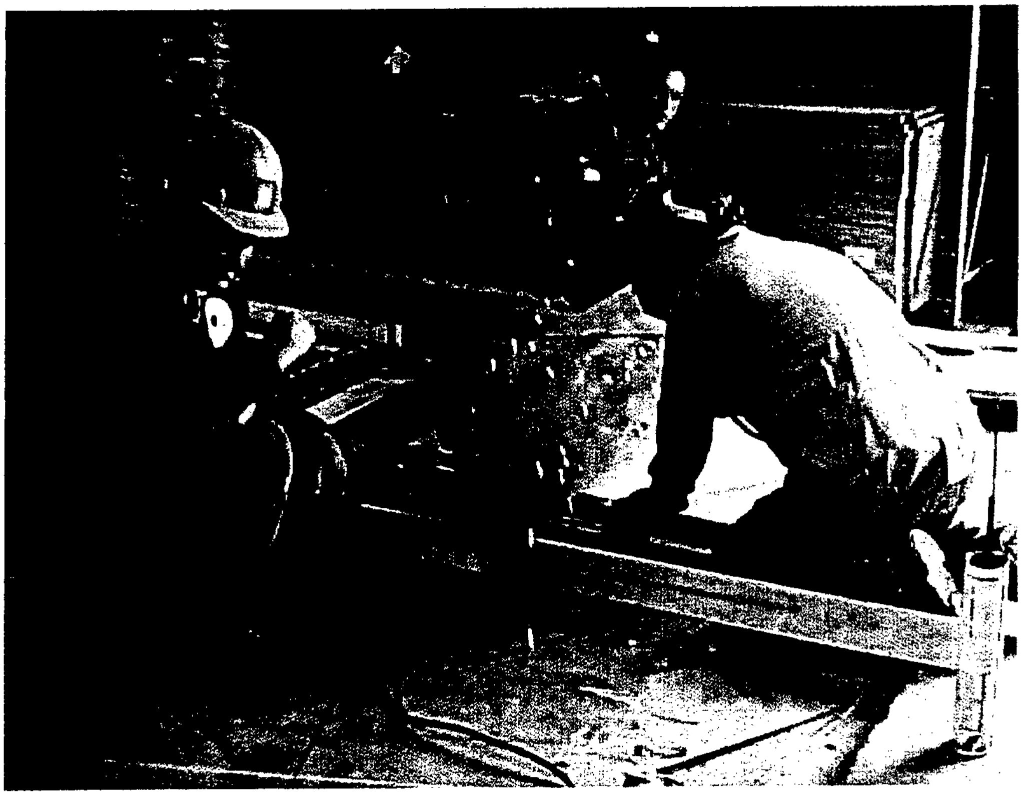


Figure 5. Welding arrangement for damage.

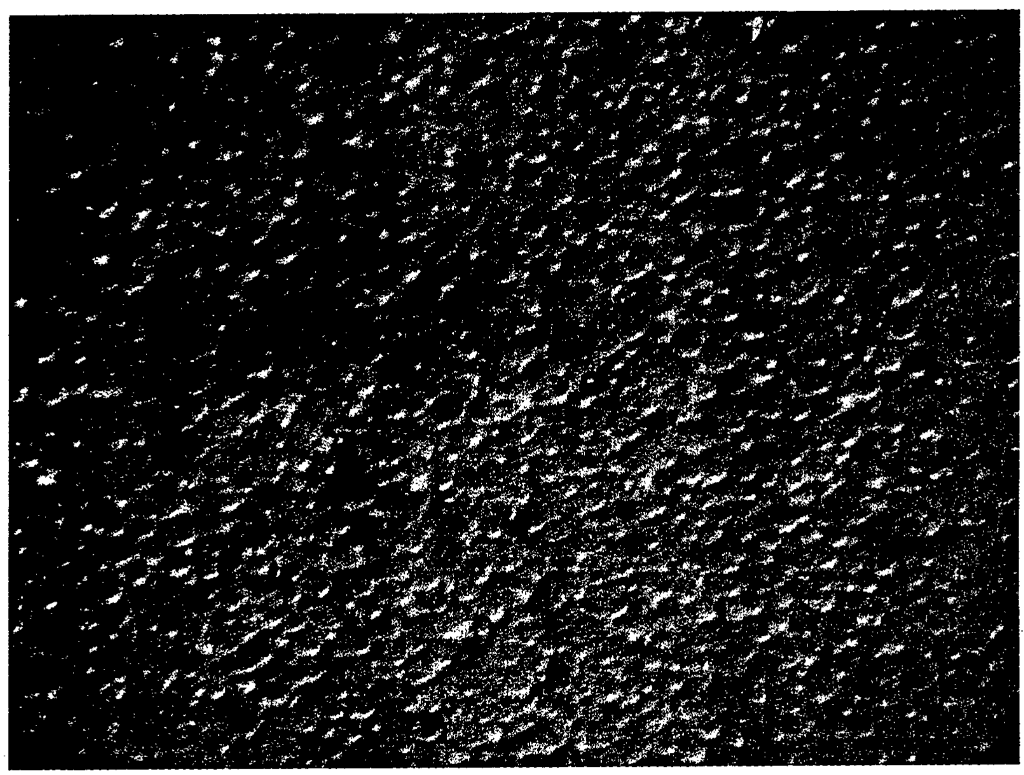


Figure 6. Photograph of damage.

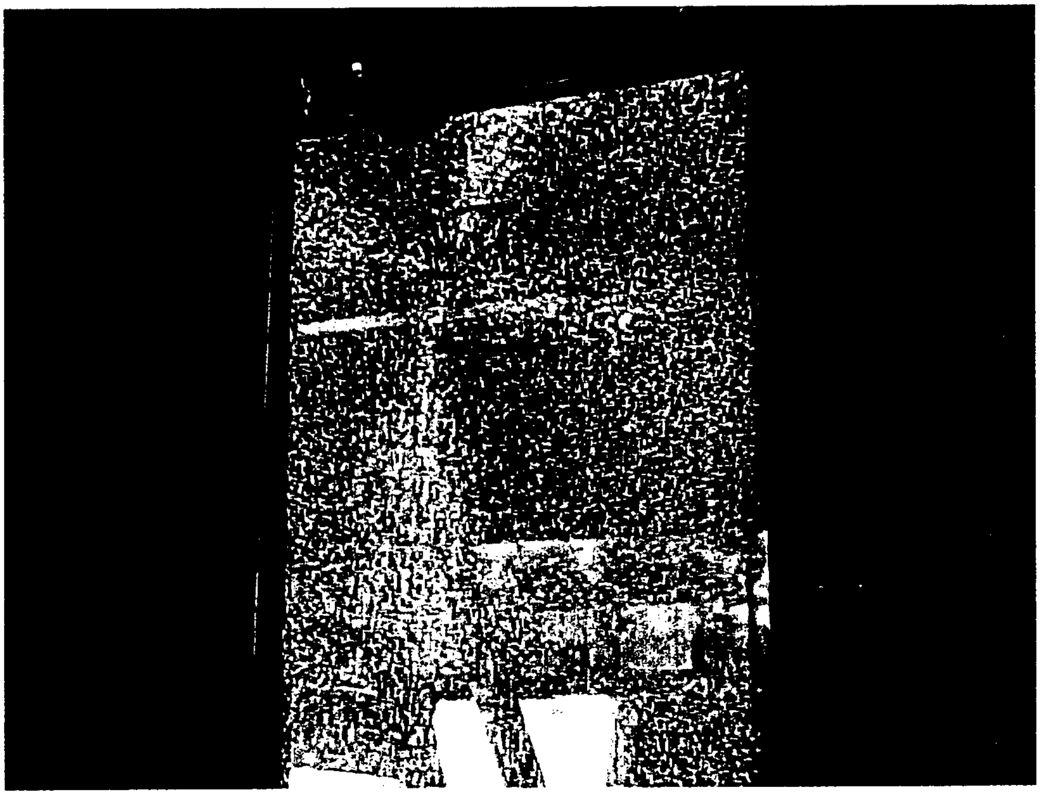


Figure 7. Photograph of fractured glazing.

Figure 8. Photograph of damage to the glazing.

- The document, "Thermal Radiation Test Supplement to Fire Resistance Tests for 'A,' 'B,' and 'F' Class Divisions (Part A: Unrestricted Usage) (IMO, 1998b) was applied.
- The fire test was terminated after 35 minutes.

Instrumentation

Ten thermocouples were used to monitor and control the test exposure. They were symmetrically aligned inside the test furnace to determine if the furnace was providing a uniform exposure to the test assembly. The specified time/temperature curve was followed during the test.

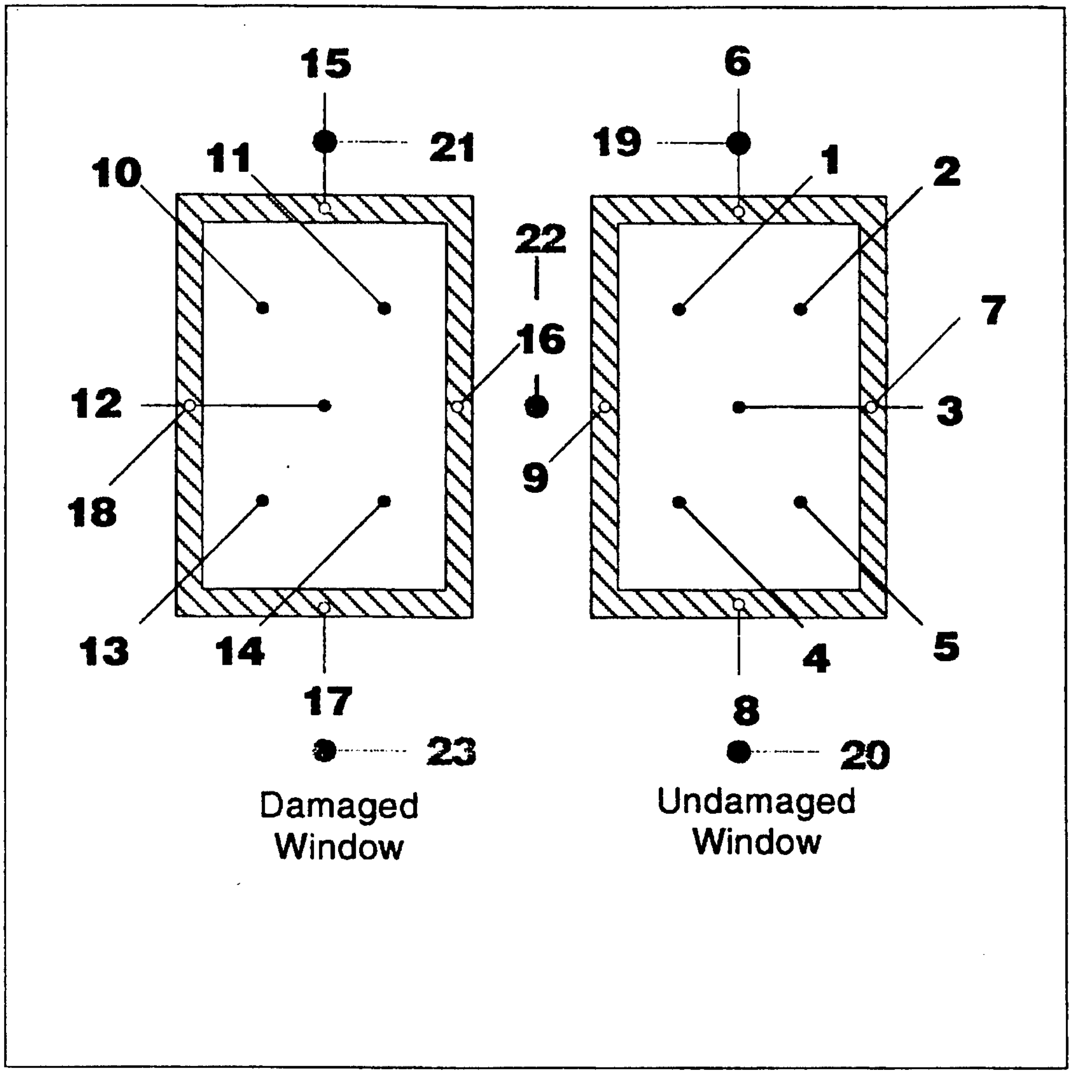
The furnace pressure was also measured inside the furnace during the test.

Unexposed surface temperature measurements are shown in figure 9 and consisted of the following:

- Window frame measurements – total of four per window: one thermocouple at the mid-length of each frame edge.
- Window surface – total of five per window: one thermocouple in the center of the window and one at the center of each quadrant of the window.
- Unexposed side of the bulkhead – total of five required.

Heat flux measurements to determine the radiation passing through the window glazing were also performed. This was accomplished using two calibrated Medtherm, restricted view (30°) heat flux gauges.[3] One gauge per window assembly was used, and each gauge was mounted external to the window assembly at a distance of 1321 mm (52 in) from the unexposed face of the window assembly. This provided a 762 mm (30 in) diameter view of the glazing during the test.

[3] The gauges are on the inventory of the U.S. Coast Guard R&D Center. Heat flux gauge no. 74048 was used on the damaged window, and heat flux gauge no. 74049 was used on the undamaged window.



Note:
Thermocouples were placed at the locations indicated and held in place with silicone adhesive. The thermocouple assemblies were thin copper disks with 24 GA. type K thermocouple wires welded to the back and covered with a thin ceramic fiber pad.

TCs 1–5 and 10–14 were located on the unexposed surface of the glass. TCs 6–9 and 15–18 were located on the unexposed surface of the window frames. TCs 19–23 were located on the surface of the steel bulkhead.

Figure 9. Thermocouple layout.

Testing

On May 12, 1999, a fire test was conducted on a test bulkhead that incorporated two window assemblies. The damaged window was on the left side of the bulkhead, and the undamaged window was on the right side of the bulkhead as viewed from the unexposed face.

The test was conducted according to the procedures described earlier for a duration of 35 minutes.

Figure 10 provides a photograph of the exposed face of the test assembly prior to test, and figure 11 provides a photograph of the test in progress. Figures 12 and 13 provide photographs of the unexposed face at 30 minutes into the test period and of the exposed face after the tests, respectively.

Test Results

Table 1 provides a summary of the observations was made during the test. The data obtained during this test are provided in Appendix A. The test was witnessed by Mr. David E. Beene, Jr., representing the U.S. Coast Guard.

Table 1. Summary of test observations.

TIME (min:sec)	OBSERVATION
0:00	Ignition of the furnace
2:20	Gel has separated from the glass on the exposed face of the undamaged window
2:21	Gel has separated from the glass on the exposed face of the damaged window
4:38	Inner undamaged pane of glass breaks and falls away on the damaged window
4:58	Inner pane of glass breaks and falls away on the undamaged window
~5:30	Gel on both windows has turned opaque
~16:30	Gel in both windows has turned black on exposed face
35:00	Test terminated.

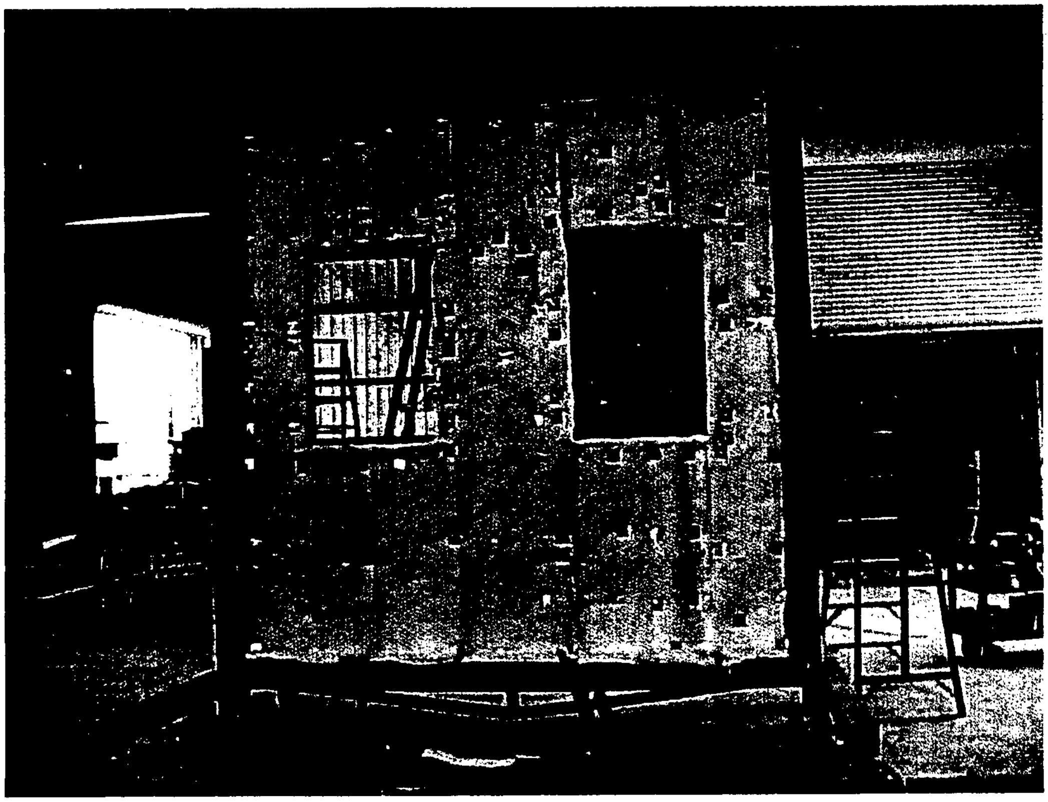


Figure 10. Photograph of exposed face – pre-test.

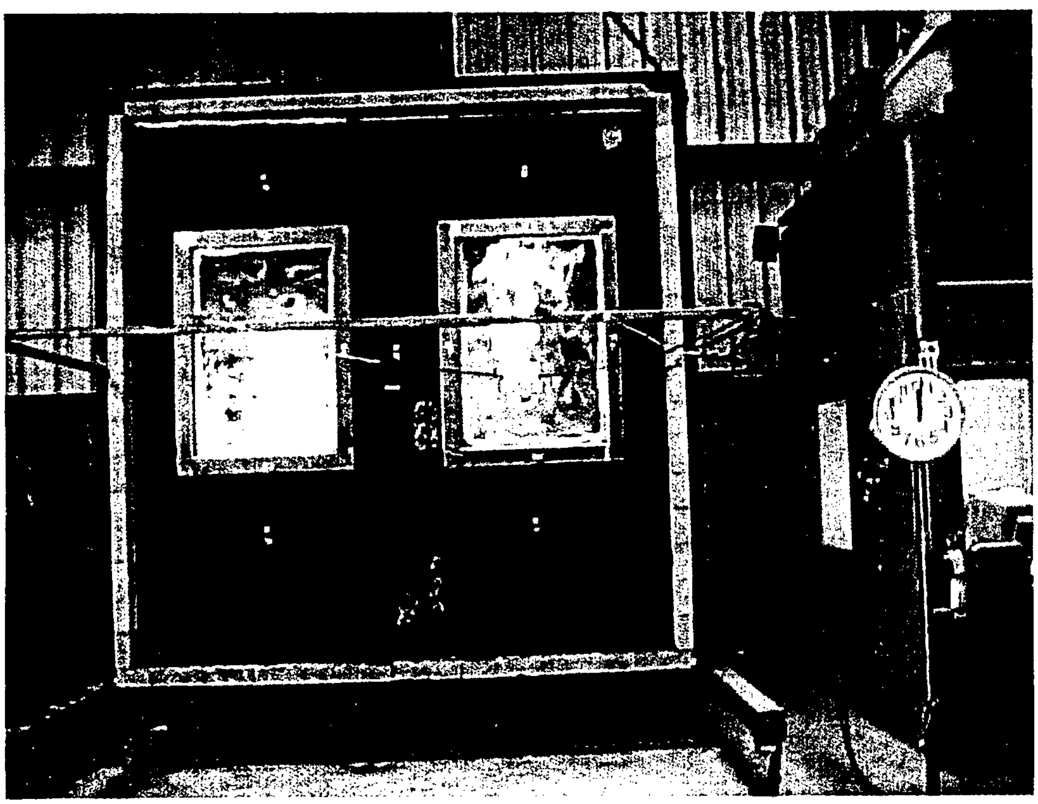


Figure 11. Photograph of test in progress.

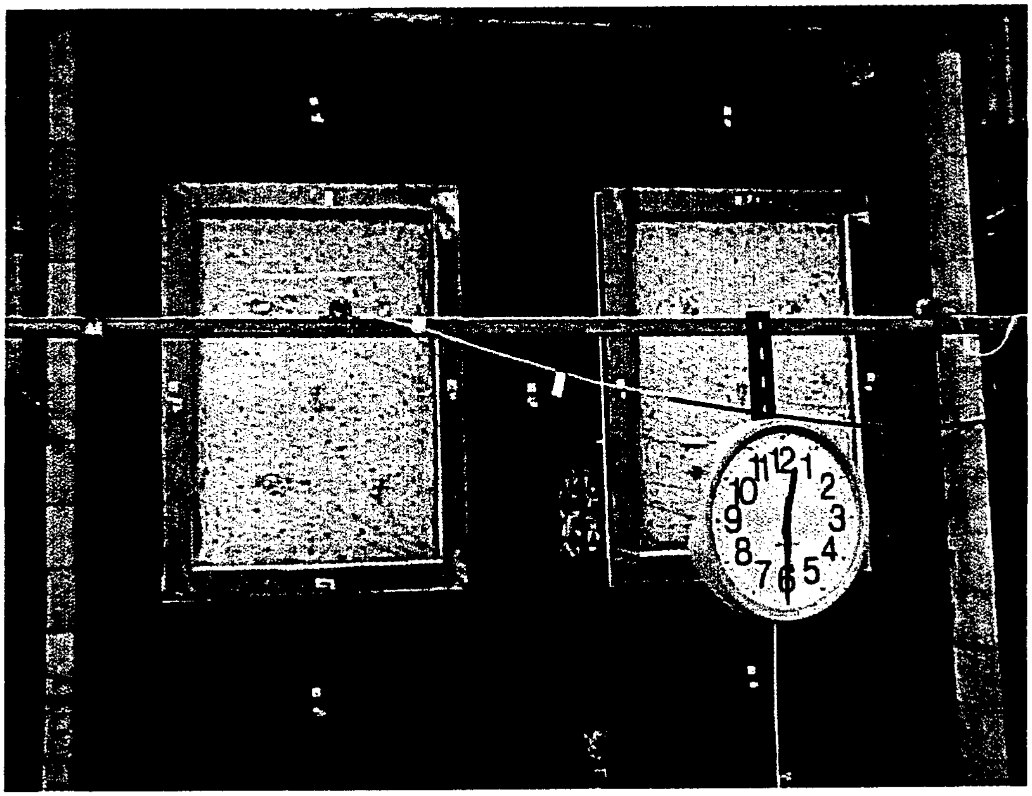


Figure 12. Photograph of unexposed face at 30 minutes.

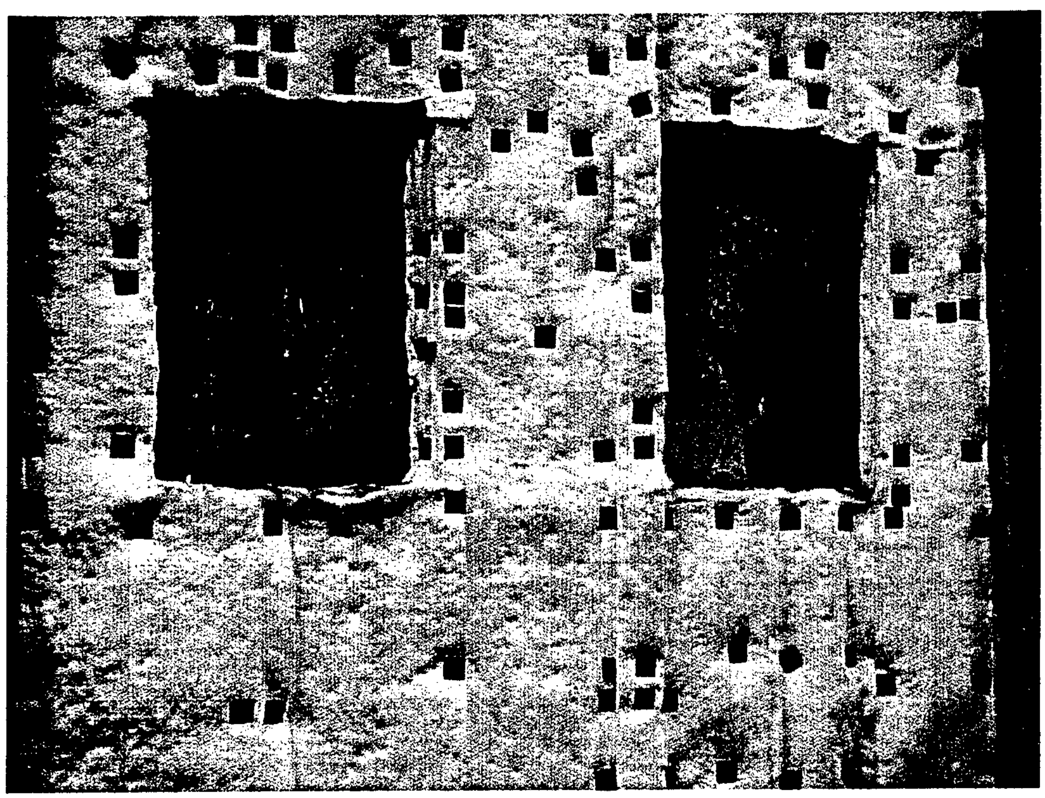


Figure 13. Photograph of exposed face – post-test.

During the test, the exposed layer of glass did fracture and fall from both of the assemblies. The gel did react to the heat, and it formed a char layer. The glass on the unexposed face of both window assemblies did not fracture or fall away.

ANALYSIS

Both the damaged and the undamaged window assemblies met the A-30 requirement of limiting the temperature rise for 30 minutes. The maximum measured heat fluxes were 0.9 kW/m^2 on the damaged window and 0.1 kW/m^2 on the undamaged window. These values were measured at the 35 minutes into the test period. In addition, on both the damaged and the undamaged windows, the unexposed side of the glazing, as well as the frame assembly, remained intact during the test.

Based on these test results as well as the lack of a fourth window (i.e., fractured earlier, thus no control window was available), it was decided that a second test would not be performed.

The results of this test did not substantiate the hypothesis that welding splatter would cause a premature failure of the window. The failure of the glass that was damaged in the horizontal configuration may suggest, however, a potential failure mechanism.

Glass is a homogenous, isotropic material, and since glass fails suddenly without permanent deformation, it is considered a brittle material. In general, glass failure results from a tensile stress in combination with a defect or surface flaw (Gangnath, 1999). This behavior was noted in the failure of the horizontally damaged window.

The depth of the surface flaw (i.e., damage by the welding slag) could explain the premature failure of the horizontally damaged window. The horizontal orientation used to damage the window allowed the hot slag to remain on the surface of the glazing for a longer period of time than the slag used to damage the vertically orientated window. This longer time element allowed the slag to damage (pit) the horizontal glazing to a greater depth than in the case of the vertical window. When damaging the vertical window, the hot welding slag would hit the

glazing and bounce off, which caused pits to form; however, these pits had a lesser depth than those formed on the horizontal glazing. These observations, along with the test results, would suggest that the depth of the damage to the glazing is an important factor in the failure of the glazing.

The testing did show that if the glazing is damaged from pitting by welding slag, it may continue to perform as required in a fire test. The amount (i.e., depth, size) of the damage is a critical factor.

This work pointed out that the use of welding slag as a damage technique would not provide a reproducible method for damaging glazing. This technique does not control the number of pits created nor does it allow control of either the size or the depth of the damage. This lack of reproducibility may be a factor with regards to the failures observed in the previous tests. The observed failures were consistently between eight and ten minutes into the test; this is inconsistent with the variability in the damage caused by welding slag.

Based on this work and since the other postulated failure mode (i.e., incorrect installation) was not evaluated, no definitive conclusion can be drawn concerning the failures observed in the previous testing.

SUMMARY

In a previous test series, two of four A-30 windows and one of four A-60 window assemblies failed within eight and ten minutes after the beginning of the test exposure. The suspected causes were incorrect installation or damage by welding slag from the attachment of thermocouples to the window frame.

The issue of incorrect installation could not be investigated due to the unavailability of the frame used in the previous test series. The new frame did not have a top and bottom orientation.

A fire resistance test was conducted, in which both an undamaged and a damaged (via welding slag) window were evaluated. The test showed that both of the windows met the A-30 requirement of limiting the temperature rise for 30 minutes.

The failure of a window assembly during its mounting in a bulkhead indicates that the damage (i.e., size and depth of pits) may be a significant factor in its failure mechanism during a fire situation. The test also indicates that an A-30 window assembly may perform appropriately even with some damage on the unexposed face of the glass.

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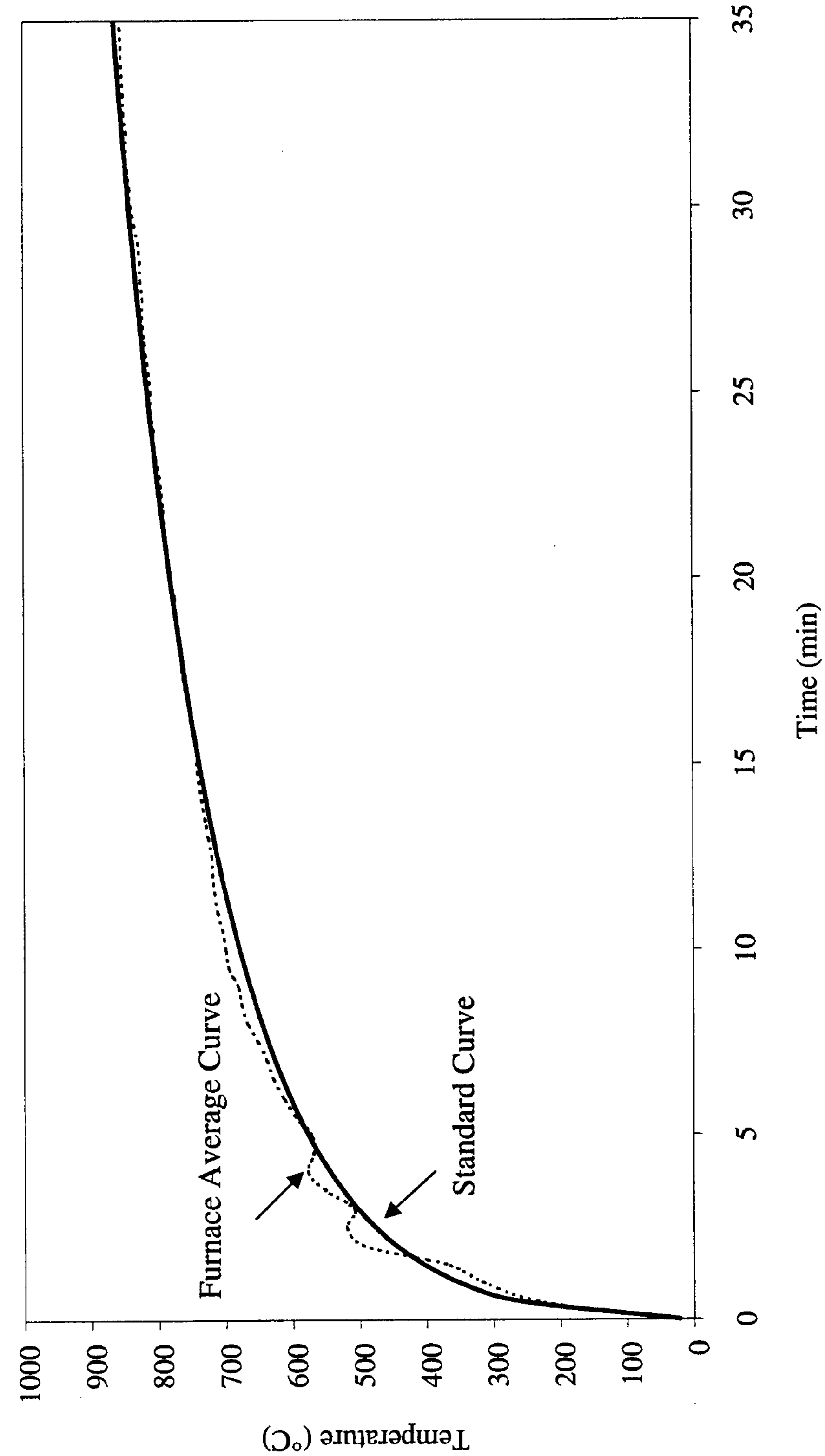
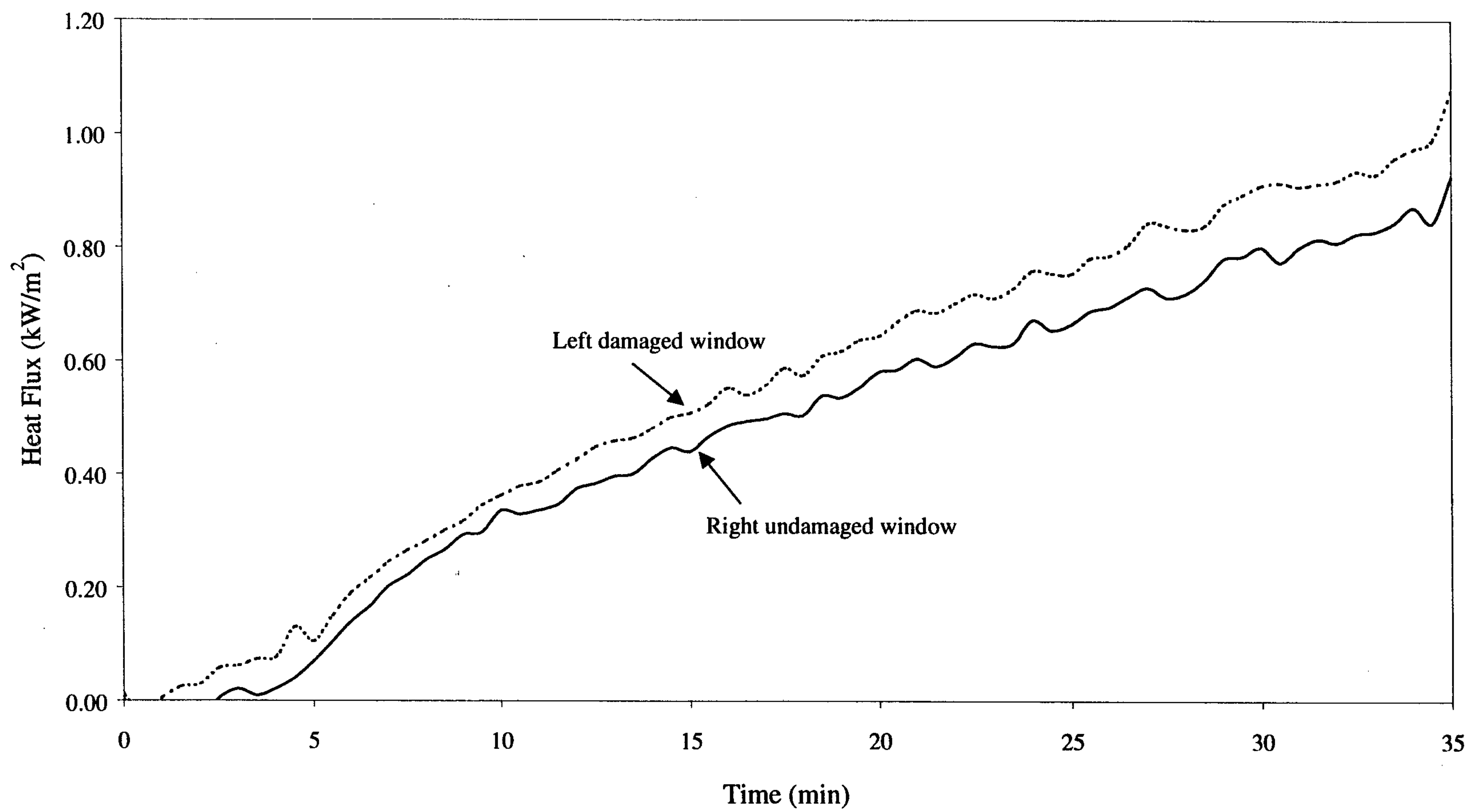
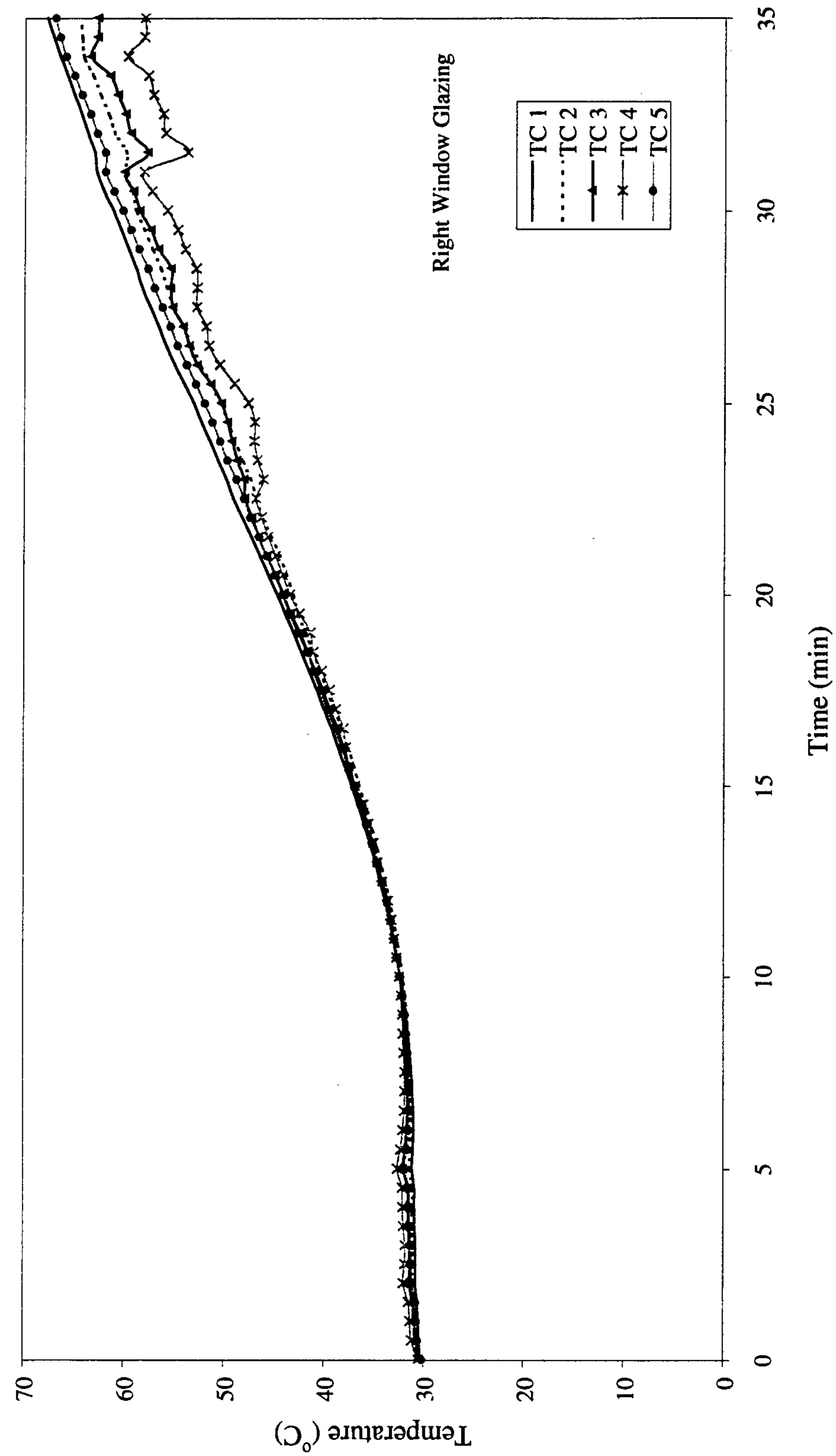
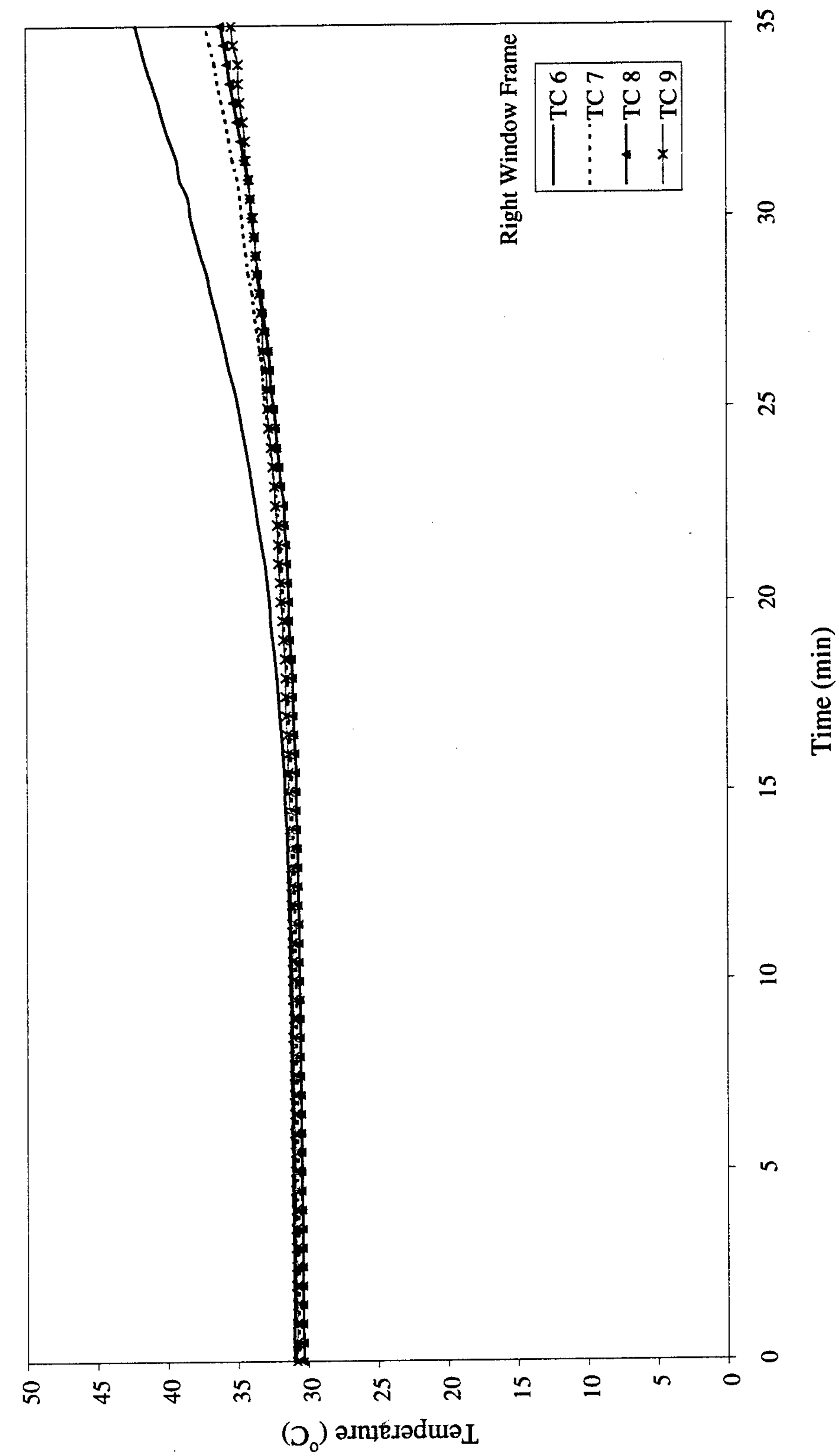
APPENDIX A – TEST DATA

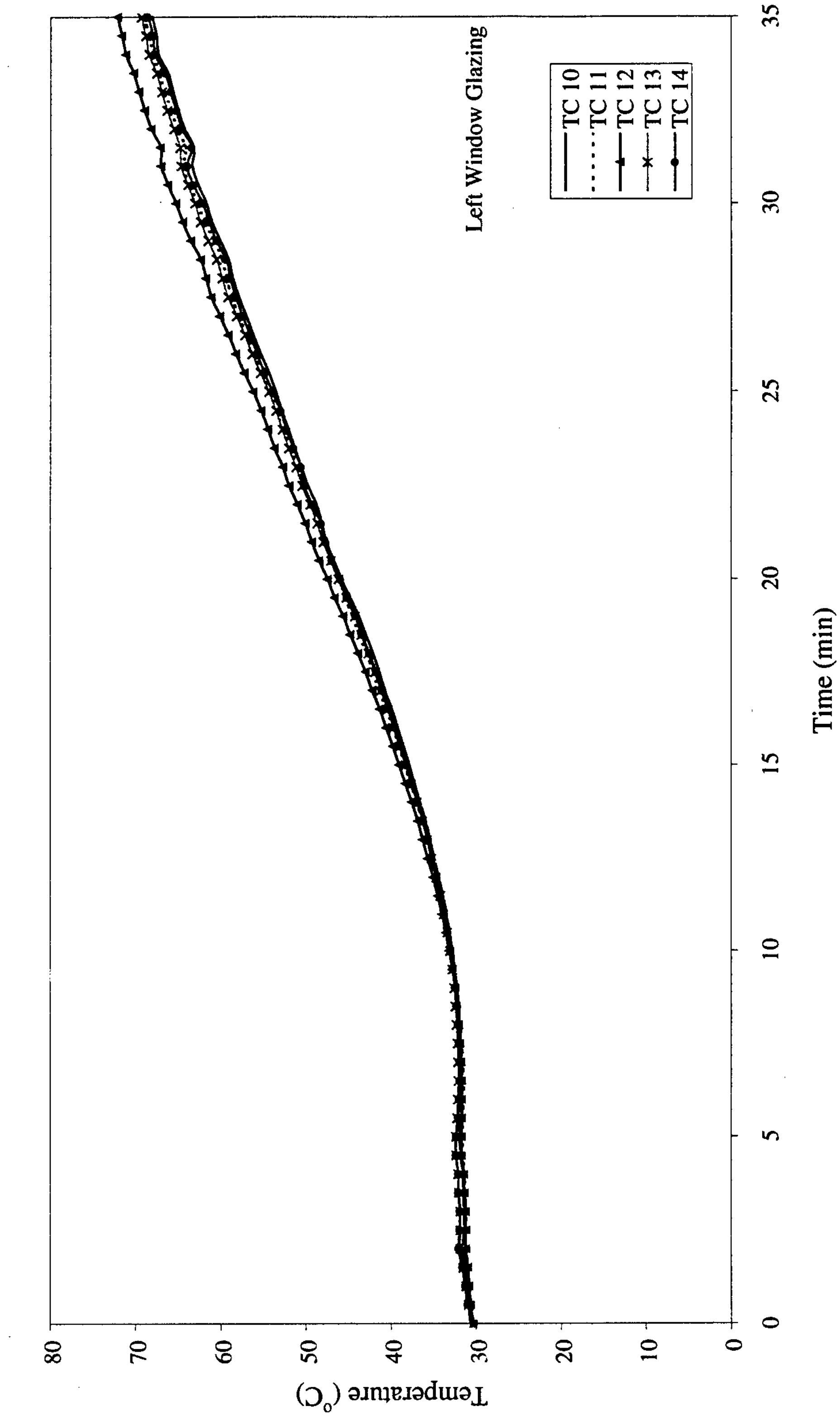


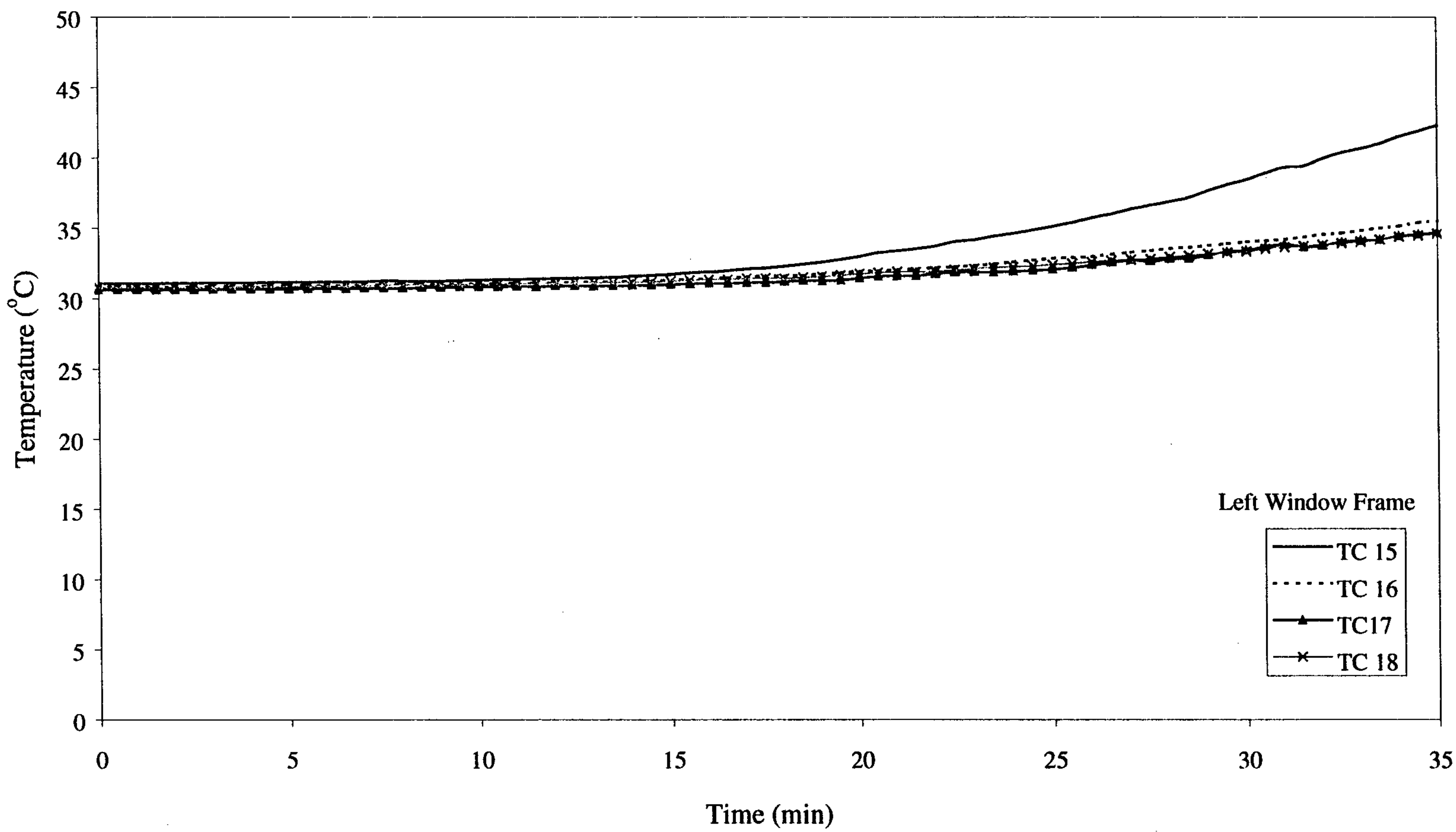

1.20
1.00
0.80
0.60
0.40
0.20
0.00
Heat Flux (kW/m2)
Left damaged window
Right undamaged window
0
5
10
15
20
25
30
35
Time (min)

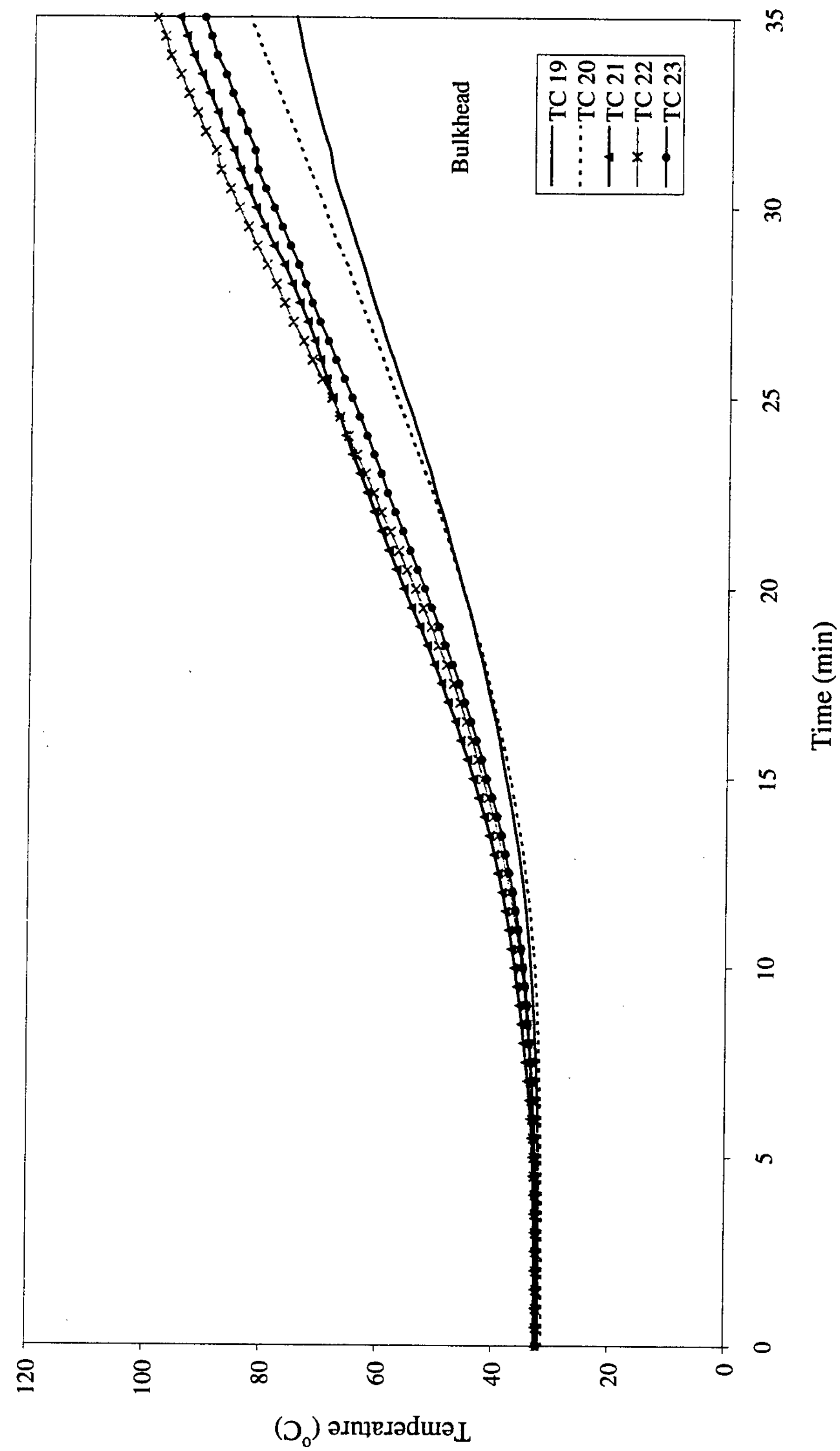

Right Window Glazing
TC 1
TC 2
TC 3
TC 4
TC 5
Temperature (°C)
Time (min)
70
60
50
40
30
20
10
0
5
15
25
35



Right Window Frame
TC 6
TC 7
TC 8
TC 9
Temperature (°C)
Time (min)
0
5
10
15
20
25
30
35
40
45
50


Left Window Glazing
TC 10
TC 11
TC 12
TC 13
TC 14
Time (min)
Temperature (°C)
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
70
80


50
45
40
35
30
25
20
15
10
5
0
Temperature (°C)
0
5
10
15
20
25
30
35
Time (min)
Left Window Frame
TC 15
TC 16
TC17
TC 18



Bulkhead
TC 19
TC 20
TC 21
TC 22
TC 23
Temperature (°C)
Time (min)
0
20
40
60
80
100
120
0
5
10
15
20
25
30
35